Patent Application of

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for

Diode Device

Background: Related Application

This is a Continuation in Part of a Continued Prosecution Application filed 3 March 1998 of U.S. Pat. Appl. No. 08/924,910, filed 8 September 1997.

This application is also related to "Method for Increasing Emission through a Potential Barrier" by Tavkheldize, filed 31 August 1998 as a Continuation in Part of a Continuation in Part filed 29 June 1998 of U.S. Pat. Appl. No. 09/020,654, filed 9 February 1998, and assigned to the same assignee as the present invention.

Background: Field of Invention

The present invention is related to diode devices, in particular, to diode devices in which the separation of the electrodes is set and controlled using piezo-electric, electrostrictive or magnetostrictive positioning elements. These include thermionic converters and generators, photoelectric converters and generators, and vacuum diode heat pumps. It is also related to thermotunnel converters.

Background: Thermionic Generators

One form of thermionic vacuum diode is the thermionic converter. A problem associated with the design of these is the space-charge effect, which is caused by the electrons themselves as they leave the cathode. The emitted electrons have a negative charge that deters the movement of other electrons towards the anode. Theoretically the formation of the space-charge potential barrier may be prevented in at least two ways: positive ions may be introduced into the cloud of electrons in front of the cathode, or the spacing between the electrodes may be reduced to the order of microns.

The use of positive ions to reduce space charge is not without problems. Although cesium and auxiliary discharge thermionic converters have been described, they do not have high efficiency, are costly to fabricate, and, particularly in the high-pressure ignited mode, do not have a long life. The technique of introducing a cesium plasma into the electrode space brings with it further disadvantages. These include heat exchange reactions within the plasma during the operation of the device, and the reactivity of the plasma, which can damage the electrodes.

Although Fitzpatrick (U.S. Pat. No. 4,667,126) teaches that "maintenance of such small spacing with high temperatures and heat fluxes is a difficult if not impossible technical challenge", in an article entitled "Demonstration of close-spaced thermionic converters", 28th Intersociety Energy

Conversion Engineering Conference, Vol. 1, pages 1573 - 1580, he goes on to disclose a close spaced thermionic energy converter which operates at temperatures of 1100 to 1500 K at a variety of cesium pressures. Electrodes are maintained at a separation of the order of 10 µm by 3 ceramic spacers mounted on the collector. With electrodes at 1300 and 800 K, conversion efficiencies of 11.6% were obtained. It utilizes advanced monocrystal materials to achieve reliable operation and long life, and produces a reasonable output power with good efficiency at lower temperatures where typical ignited mode devices would produce no useful power at all. It is therefore useful at the bottom end of cascaded thermionic systems, with a very high temperature barium-cesium thermionic converter at the top end.

To operate a converter with a gap spacing of less than 10 µm, the electrode surface must be very flat and smooth, with no deformation larger than about 0.2 µm. This places a limitation on the practical size of electrodes for the emitter and collector, because heat flux through the surfaces causes a differential thermal expansion from one side relative to the other, leading to thermal expansion-caused deformation into a "dome-like" shape. This issue is even more important in high power operation. Although this deformation can be tolerated if the diameter of the electrodes is very small, the devices described by Fitzpatrick have diameters of several centimeters. Another issue is degradation of the in-gap spacers at high

emitter temperatures.

Fitzpatrick addresses both these in a later paper, entitled "Close-spaced thermionic converter with active control and heat-pipe isothermal emitters", 31st Intersociety Energy Conversion Engineering Conference, Vol. 2, pages 920 - 927. He proposes a device having a large isothermal emitter, utilizing a heat pipe built into its structure with a single crystal emitting surface. The proposed device avoids degradation of the in-gap spacers at high emitter temperatures by using active spacing control, utilizing piezo electric actuators in conjunction with feedback control for continuously adjusting the gap size.

The proposed device, however, is relatively large, expensive and not amenable to mass-production. There remains a need, therefore, for a thermionic generator which is easy to fabricate, inexpensive, reliable, of high efficiency, modular, compact and having an extended life.

For example, the alternator of the automobile could be replaced by a thermionic generator using the heat contained in the exhaust gases as a source of energy, which would lead to an increase in the efficiency of the engine. Svensson and Holmlid, in their paper entitled :TEC as Electric Generator in an Automobile Catalytic Converter" 31st Intersociety Energy Conversion Engineering Conference, Vol. 2, pages 941 - 944, propose the possible use of carbon covered electrodes which become coated with Rydberg matter, resulting in the reduction of the interelectrode distance. They report that such a device

might be expected to have an efficiency of 25 - 30% at temperatures of 1500 -1600 K. To obtain the high temperatures required, a fuel mixture would be injected into the device. Different configurations are discussed, but it is not clear how such a device would be economically constructed.

Another application is in domestic and industrial heating systems. These need a pump to circulate heated water around the system, which requires a source of power. The control circuitry regulating the temperature of the building being heated also requires power. These could both be supplied by means of a thermionic generator powered by the hot flue gases.

A further application utilizes heat generated by solar radiation. This could either be in space or earth-based solar power stations, or on the roof of buildings to supply or augment the power requirements of the building.

In Edelson's Patent Application, filed 1997 January 27, titled "Method and Apparatus for Thermionic Converter", serial number 08/790,753, assigned to the same assignee as the present invention, and incorporated herein in its entirety by reference, a thermionic converter having close spaced electrodes is disclosed which is fabricated using micromachining techniques. This device addresses many of the problems described above, particularly those relating to economic fabrication and how to achieve close spaced electrode design. However, in operation, temperature differences between the hot emitter and cooler collector may cause high thermal stresses leading to the shape

of the region between the electrodes being altered.

The present invention extends the robustness of Edelson's previous device without detracting from its ease and economy of fabrication by allowing it actively to respond to these high thermal stresses by means of active piezoelectric, electrostrictive or magnetostrictive elements incorporated to produce a micro-electromechanical thermionic converter.

Background: Thermotunnel Converter

The thermotunnel converter is a means of converting heat into electricity which uses no moving parts. It has characteristics in common with both thermionic and thermoelectric converters. Electron transport occurs via quantum mechanical tunneling between electrodes at different temperatures. This is a quantum mechanical concept whereby an electron is found on the opposite side of a potential energy barrier. This is because a wave determines the probability of where a particle will be, and when that probability wave encounters an energy barrier most of the wave will be reflected back, but a small portion of it will 'leak' into the barrier. If the barrier is small enough, the wave that leaked through will continue on the other side of it. Even though the particle does not have enough energy to get over the barrier, there is still a small probability that it can 'tunnel' through it.

The thermotunneling converter concept was disclosed in U.S. Patent No. 3,169,200 to Huffman. In a later paper entitled

"Preliminary Investigations of a Thermotunnel Converter", [23rd Intersociety Energy Conversion Engineering Conference vol. 1, pp. 573-579 (1988)] Huffman and Haq disclose chemically spaced graphite layers in which cesium is intercalated in highly orientated pyrolitic graphite to form a multiplicity of thermotunneling converters in electrical and thermal series. In addition they teach that the concept of thermotunneling converter was never accomplished because of the impossibility of fabricating devices having electrode spacings of less than 10 µm. The current invention addresses this shortcoming by utilizing one or more piezo-electric, electrostrictive or magnetostrictive elements to control the separation of the electrodes so that thermotunneling between them occurs.

A further shortcoming of the devices described by Huffman is thermal conduction between the layers of the converter, which greatly reduces the overall efficiency of these thermotunnelling converters.

Background: Photoelectric Converter

In Edelson's application filed 12th May 1997, titled "Method and Apparatus for Photoelectric Generation of Electricity", serial number 08/854,302, assigned to the same assignee as the present invention, and incorporated herein by reference, is described a Photoelectric Generator having close spaced electrodes separated by a vacuum. Photons impinging on the emitter cause electrons to be emitted as a consequence of

the photoelectric effect. These electrons move to the collector as a result of excess energy from the photon: part of the photon energy is used escaping from the metal and the remainder is conserved as kinetic energy moving the electron. This means that the lower the work function of the emitter, the lower the energy required by the photons to cause electron emission. A greater proportion of photons will therefore cause photo-emission and the electron current will be higher. The collector work function governs how much of this energy is dissipated as heat: up to a point, the lower the collector work function, the more efficient the device. However there is a minimum value for the collector work function: thermionic emission to the collector will become a problem at elevated temperatures if the collector work function is too low.

Collected electrons return via an external circuit to the cathode, thereby powering a load. One or both of the electrodes are formed as a thin film on a transparent material, which permits light to enter the device. A solar concentrator is not required, and the device operates efficiently at ambient temperature.

Vacuum Diode-Based Devices

In Edelson's disclosure, filed 1995 July 5, titled "Method and Apparatus for Vacuum Diode Heat Pump", serial number 08/498,199, assigned to the same assignee as the present invention, incorporated herein in its entirety by reference, a new use for thermionic vacuum diode technology is disclosed wherein a vacuum diode is constructed using very low work function electrodes. A negative potential bias is applied to the cathode relative to the anode, and electrons are emitted. In the process of emission, the electrons carry off kinetic energy, carrying heat away from the cathode and dissipating it at an opposing anode. The resulting heat pump is more efficient than conventional cooling methods, as well as being substantially scaleable over a wide range of applications. Fabrication using conventional techniques is possible.

Background: Piezoelectric Positioning Elements

Piezoelectric worm-type shifting mechanisms, or piezo motors, can move extremely short distances of the order of a single Angstrom, while having a stroke of several tens of millimeters.

Scanning Tunneling Microscopes are well known for employing piezoelectric devices to maintain tip distance from a surface to an accuracy of 1 angstrom.

U.S. Pat. No. 4,423,347 to Kleinschnidt et al. discloses a type of electrically actuated positioning element formed of piezo-electric bodies, which may, for example, be used to

operate a needle valve.

U.S. Pat. No. 5,351,412 to Furuhata and Hirano discloses a device which provides micro-positioning of the sub-micron order.

U.S. Pat. No. 5,049,775 to Smits discloses an integrated micro-mechanical piezo-electric motor or actuator. This has two parallel cantilever beams coated with a piezo-electric material and attached to a body to be moved at one end, and to a V-shaped foot at the other. By applying an electric field, the foot may be raised, twisted, lowered and straightened, providing movement. An example has a device with cantilever beams 1 x 10 x 200 µm which can move at 1 cm/s.

The above illustrate that piezo-electric elements may be fabricated and used at micron and sub-micron scale and that they are useful for positioning objects with great accuracy. Fitzpatrick takes advantage of these features in his proposed close spaced thermionic converter. He does not teach, however, that micro-mechanical devices such as that disclosed by Smits may be adapted to form a useful function in positioning the electrodes in a micromachined thermionic vacuum diode.

Background: Electostrictive and magnetostrictive positioning elements

Razzaghi (U.S. Pat. No. 5,701,043) teaches that some commercially available magnetostrictive materials readily produce strains 10 times higher than that of electroactive materials such as piezoelectric or electrostrictive elements. They are also superior with respect to load, creep, sensitivity

to temperature and working temperature range. He discloses a high resolution actuator using a magnetostrictive material able to achieve displacements with subnanometer resolution and a range of about 100 µm.

Visscher (U.S. Pat. No. 5,465,021) disclose an electromechanical displacement device which uses piezoelectric, electrostrictive or magnetostrictive clamping and transport elements.

Takuchi (U.S. Pat. No. 5,592,042) disclose a piezoelectric or electrostrictive actuator of bi-morph or uni-morph type, and teach that it may be useful as a displacement controllable element, an ink jet ejector, a VTR head, a switching element, a relay, a print head, a pump, a fan or blower.

Kondou (U.S. Pat. No. 5,083,056) disclose an improved circuit for controlling a bimorph-type electrostriction actuator.

Hattori (U.S. Pat. No. 4937489) disclose an electrostrictive actuator for controlling fine angular adjustments of specimens under microscopic scrutiny.

Background: Surface Polishing

It is known to the art that over a 1 cm distance length, a surface can be polished to a fraction of a micron. However, the art provides no methods for providing surfaces which are flat to the order of tens of angstroms. Additionally, the art provides no methods of making electrodes which match each other's surface

features, thus providing 2 surfaces which are flat relative to one another. The present invention discloses and claims such a technique, which allows for very close spacing between electrodes.

Definitions:

"Power Chip" is hereby defined as a device which uses a thermal gradient of any kind to create an electrical power or energy output. Power Chips may accomplish this using thermionics, thermotunneling, or other methods as described in this application.

"Cool Chip" is hereby defined as a device which uses electrical power or energy to pump heat, thereby creating, maintaining, or degrading a thermal gradient. Cool Chips may accomplish this using thermionics, thermotunneling, or other methods as described in this application.

"Gap Diode" is defined as any diode which employs a gap between the anode and the cathode, or the collector and emitter, and which causes or allows electrons to be transported between the two electrons, across or through the gap. The gap may or may not have a vacuum between the two electrodes, though Gap Diodes specifically exclude bulk liquids or bulk solids in between the anode and cathode. The Gap Diode may be used for Power Chips or Cool Chips, for devices that are capable of operating as both Power Chips and Cool Chips, or for other diode applications.

Surface features of two facing surfaces of electrodes

"matching" each other, means that where one has an indentation, the other has a protrusion and vice versa. Thus the two surfaces are substantially equidistant from each other throughout their operating range.

Brief Description of the Invention

The present invention discloses, in one preferred embodiment, a Gap Diode fabricated by micromachining techniques in which the separation of the electrodes is controlled by piezo-electric, electrostrictive or magnetostrictive actuators. Another preferred embodiment is a Gap Diode built and operated by MicroEngineeringMechanicalSystems, or MEMS, and its equivalents, in which the separation of the electrodes is controlled by piezo-electric, electrostrictive or magnetostrictive actuators.

The present invention further discloses a Gap Diode in which the separation of the electrodes is controlled by piezo-electric, electrostrictive or magnetostrictive actuators. Preferred embodiments include Cool Chips, Power Chips, and photoelectric converters. In further embodiments, Gap Diodes may be fabricated using micromachining techniques, and include MicroEngineeringMechanicalSystems, or MEMS versions, or their equivalents, in which the electrode separation is controlled by piezo-electric, electrostrictive or magnetostrictive actuators.

In a further embodiment, the present embodiment Gap Diodes in which the separation of the electrodes is controlled by piezo-electric, electrostrictive or magnetostrictive actuators,

and where the space between the electrodes is filled with an inert gas: according to this embodiment the separation of the electrodes is less than the free mean path of the electrons in the inert gas. This means that thermal conduction between the electrodes is almost entirely eliminated.

In operation, temperature differences between the emitter or cathode electrode, and the collector or anode electrode, of the Gap Diode may cause high thermal stresses leading to the space between electrodes being altered. These thermal stresses may also cause the electrodes to flex, buckle or otherwise change their shape. The present invention addresses these problems by utilizing a piezo-electric, electrostrictive, or magnetostrictive element to control the separation of the electrodes. Furthermore the present invention discloses utilizing a piezo-electric, electrostrictive, or magnetostrictive element to alter the shape of the electrodes to overcome flexing, buckling or shape-changing thermal stresses.

The present invention further discloses a method for fabricating a pair of electrodes in which any minor variations in the surface of one electrode are replicated in the surface of the other. This permits the electrodes to be spaced in close proximity.

A method of selecting materials is disclosed which can be used to compensate for thermal expansion. This method is optimal for use in thermotunneling Power Chips and Cool Chips, and also has uses in especially close-spaced thermionic Power Chips and

Cool Chips.

The present invention further discloses the concept of employing electron tunneling in a Cool Chip.

These devices overcome disadvantages of prior art systems such as economy and ease of fabrication and problems introduced by heat distortion at high temperature operation.

OBJECTS AND ADVANTAGES

The present invention comprises one or more of the following objects and advantages:

It is an object of the present invention to provide Gap Diodes or Power Chips or Cool Chips in which the separation of the electrodes is controlled by piezo-electric, electrostrictive or magnetostrictive actuators.

An advantage of the present invention is that alterations to the spacing of the electrodes which may happen as a consequence of the large temperature difference between the electrodes may be nullified.

A further advantage of the present invention is that a less demanding manufacturing specification is required.

A further advantage of the present invention is that the resulting Gap Diode will be extremely resistant to vibration and shock, as the actuators can rapidly counteract any such stresses.

It is a further object of the present invention to provide

Power Chips or Cool Chips or Gap Diodes in which the separation of the electrodes is reduced to micron or sub-micron distances, and is maintained at this small distance through the action of piezo-electric, electrostrictive or magnetostrictive actuators.

An advantage of this invention is that space charge effects are reduced.

Another advantage of this invention is that changes in electrode separation due to thermal changes occurring as the device is operated may be compensated.

It is a further object of the present invention to provide Gap Diodes or Cool Chips or Power Chips in which the separation of the electrodes is small enough to allow electrons to tunnel between cathode and anode, and in which this small separation between electrodes is maintained through the action of piezo-electric, electrostrictive or magnetostrictive actuators.

An advantage of this invention is that the efficiency of the inter-converter is substantially increased.

An advantage of this invention is that heat can be efficiently pumped from one electrode to another.

An advantage of this invention is that a temperature differential can be used to generate electricity.

An advantage of this invention is that a low work function electrode is not required.

An advantage of this invention is that, when it is used to pump heat, it can cool down to 1 degree Kelvin.

It is a further object of the present invention to provide Gap Diodes in which the separation of the electrodes is less than the free mean path of an electron, and in which this small separation between electrodes is maintained through the action of piezo-electric, electrostrictive or magnetostrictive actuators.

An advantage of this invention is that the space between the electrodes may be filled with an inert gas.

An advantage of this invention is that thermal conduction between the electrodes is substantially reduced, and the efficiency of the device is substantially increased.

It is a still further object of the present invention to provide Gap Diodes fabricated using micromachining techniques in which the separation between electrodes is maintained through the action of piezo-electric, electrostrictive or magnetostrictive actuators.

An advantage of this invention is that the devices may be constructed inexpensively and reliably.

It is a still further object of the present invention to provide Power Chips and Cool Chips fabricated and operated by MicroEngineeringMechanicalSystems, or MEMS in which the separation between electrodes is maintained through the action of piezo-electric, electrostrictive or magnetostrictive actuators.

An advantage of this invention is that the devices may be constructed cheaply and reliably.

It is a yet further object of the present invention to provide pairs of electrodes in which any minor imperfections in the surface of one are replicated in the surface of the other.

An advantage of this invention is that electrodes may be positioned such that the separation between them is of a very small magnitude.

An advantage of this invention is that a larger surface area can be used for pumping heat, converting heat to electricity, or any other functions of a diode.

An advantage of this invention is that benefits accruing to small spaces, such as tunneling effects, can be maximized.

It is a yet further object of the present invention to provide a method of selection of electrode materials in which the thermal expansion coefficient of the cold side is larger than that of the cold side.

An advantage of this invention is that the temperature difference between the two electrodes can be greatly increased before the electrodes touch each other due to thermal expansion.

REFERENCE NUMERALS IN DRAWINGS

1. Emitter electrode
5. Collector electrode

10. Region between an Emitter and a Collector

15. Housing

20. Piezo-electric actuator

27. Power supply/Electrical load

29. Capacitance controller

30. Thermal interface

35. Thermal interface

40. Connecting wires

70. Light beam

80. Corrugated sealing tubes

82. Metal powder infill

100. First step

102. Polished monocrystal of first electrode material

110. Second step

112. Layer of material

120. Third step

122. Thin layer of second electrode material

130. Fourth step

132. Electrochemically-grown layer of second electrode material

140. Fifth step

It should be noted in all cases that the emitter is the hot side, in a Power Chip, and the collector is the cold side, in a Power Chip. A Cool Chip, however, emits from

the cold side, and collects from the hot side. Thus, each thermal interface can be either the hot side or the cold side, depending on whether the device is operating as a Cool Chip, or as a Power Chip.

Brief Description of drawings

Figure 1 is a diagrammatic representation of one embodiment of the electrode configuration of a Gap Diode, Power Chip or Cool Chip showing a piezo-electric actuator supporting an electrode.

Figure 2 is a diagrammatic representation of one embodiment of the electrode configuration of a Gap Diode, Power Chip or Cool Chip, showing piezo-electric actuators at intervals along the under-surface of an electrode.

Figure 5 is a diagrammatic representation of one embodiment of a photoelectric Power Chip with electrode separation controlled by piezo-electric actuators.

Figure 5A is a diagrammatic representation of one embodiment of a device illustrating how heat transfer is facilitated.

Figure 6 is a schematic showing a process for the manufacture of pairs of electrodes which have approximately matching surface details.

Detailed Description of the Invention

The following description describes a number of preferred embodiments of the invention and should not be taken as limiting